A photonic crystal fibre and a method for its production.

This invention relates to a photonic crystal fibre,
to a method of making a photonic crystal fibre and to a
method of transmitting light along a photonic crystal
fibre.

Optical fibres are used for transmitting light from
one place to another. Normally, optical fibres are made
of more than one material. A first material is used to
form a central light-carrying part of the fibre known as
the core, while a second material surrounds the first
material and forms a part of the fibre known as the
cladding. Light can become trapped within the core by
total internal reflection at the core/cladding interface.
Total internal reflection in general causes no losses
other than the intrinsic absorptive and scattering losses
associated with the materials themselves. Conventional
and commercial low-loss optical fibres typically have a
total internal reflection structure; however, one
limitation of the waveguiding mechanism (which we refer to
as "index guiding") is that the refractive index of the
material forming the core must be higher than that of the
material forming the cladding, in order to achieve total
internal reflection. Even if the cladding is air (with a
refractive index of approximately unity) the core material
must still be a solid material for the fibre to be useful.
In practice, using air as the cladding material is
normally not advisable, because it does not offer
sufficient mechanical or optical protection of the
waveguiding core. Thus, conventional optical fibres
consist of a solid or liquid core material surrounded by a
solid cladding.

- 2 -

An optical fibre waveguide having a significantly different structure from that of conventional optical fibres has been demonstrated, in which a single microstructured material is used to form the fibre core

5 and cladding. The introduction of morphological microstructure into the fibre - typically in the form of an array of small holes which run down the length of the fibre - alters the local optical properties of the fibre, making it possible to design and fabricate intricate

10 waveguiding structures with most unusual properties. Such a fibre is an example of a photonic crystal fibre.

In one type of photonic crystal fibre, a fibre with a periodic array of air holes in its cross-section and with a single missing air hole in the centre (a "defect" in the

15 crystal structure) forms a low-loss all-silica optical waveguide which remains monomode for all wavelengths within the transmission window of the silica. The waveguiding mechanism in that case is closely related to that in conventional optical fibres and is a form of total

20 internal reflection from a material which has a lower apparent refractive index than that of pure silica.

Another type of waveguiding has also been demonstrated in a photonic crystal fibre with a periodic array of air holes. Light can become trapped in the

25 vicinity of an extra air hole within the photonic crystal lattice (i.e. a "low-index" lattice defect), if the photonic crystal is appropriately designed to exhibit a "photonic band gap". A photonic band gap is a range of parameters - for example, a range of frequencies or wave-

30 vectors - for which light would normally be expected to propagate in the cladding material but where there are no propagating modes due to the detail of the microstruc-turing. In fibres of that type that have been demonstrated

to date (see, for example, J.C. Knight, J. Broeng, T.A.
Birks and P. St. J. Russell, "Photonic Band Gap Guidance
in Optical Fibres", Science 282 1476 (1998)), light,
propagating along a fibre, is trapped in the vicinity of a
5   low-index defect within a fibre with a honeycomb array of
air holes, but nonetheless is strongly confined to the
high-index phase of the microstructured material. The
light is evanescent in the air, so the observed guided
mode is concentrated in the silica surrounding the extra
10   air hole at the core.

Guidance of light through hollow fibres in the form of
glass capillaries has been demonstrated, but such devices
are inherently very leaky.

A long-term goal of our research has been the creation
15   of a band-gap guiding fibre in which light is trapped
within an air hole, or some other region of lower
refractive index and is guided, without significant
leakage, in that region of lower refractive index. Losses
resulting from the fibre cladding material could be
20   largely avoided in such an arrangement. That goal has
not, however, until now proved attainable.

According to the invention, there is provided a
photonic crystal fibre comprising a region of
substantially uniform, lower refractive index which is
25   substantially surrounded by cladding which includes
regions of higher refractive index and which is
substantially periodic, characterised in that the region
of lower refractive index has a longest transverse
dimension which is longer than a single, shortest, period
30   of the cladding, whereby light can be substantially
confined in the lower index region by virtue of a photonic
band gap of the cladding material and can be guided along
the fibre whilst it is so confined.

- 4 -

We have found that use of a region of lower refractive index which is relatively large enables guidance to be achieved in the region of lower refractive index and we have made a fibre in which light is guided,
5   substantially without leakage, in a hollow core. It will be understood that the region of "lower" refractive index has a refractive index which is smaller in magnitude than the refractive index of the region of higher refractive index.

10   Such a fibre has advantages over other optical fibres; for example, performance may be much less limited by interaction (absorptive or non-linear) between the propagating light and material comprising the fibre. Some light may penetrate the higher-index material to a
15   significant extent, but most light is confined to the region of lower refractive index, which might be, for example, an air hole. Fibres according to the invention could be useful in, for example, telecommunications, environmental sensing and monitoring, high power laser
20   transmission, long wavelength transmission and in other optical devices.

The power-handling capacity of a fibre is limited by non-linear processes in the materials from which they are made. In a fibre where the light is concentrated in air,
25   and only a small proportion of its power is in glass, the power carrying capacity is much greater than in conventional fibres.

Ultra-high power single-mode transmission, possibly even of light which is strongly absorbed by silica glass
30   such as that from a CO_2 laser, is a possible application of such a fibre. High power laser light delivery is another application, which also makes use of the ability of the fibre to transmit much higher power than a

- 5 -

conventional fibre; delivery of 100 W to 1 kW to a machining head, from a large-frame laser, is, for example, a recurrent need. High power lasers represent an area with broad applications in, for example, high speed

5 printing, laser machining of materials, and possibly surgery; fibre lasers are efficient, offering a high power per kg. Their compactness, and the high quality of the beams they produce, make them very attractive in all kinds of portable laser apparatus.

10 Another application of the fibre of the invention is in telecommunications. The ability of the fibre to carry high powers would allow more light to be launched into one section of a communications link. The link could therefore be longer without optical attenuation making the

15 signal undetectably small. Such a fibre with gain (by erbium doping) could be used as a high power amplifier to act as a repeater for a chain of such links.

Another application might be atom guiding, in which individual atoms are transported along the hollow core,

20 without hitting the walls, by being "carried along" a powerful light beam.

Ultra-long path lengths of light through gases, with a single transverse mode, present significant opportunities for high resolution spectroscopy and sensing applications.

25 Fresnel reflections, which are a problem in fibre devices where light is extracted from a fibre and then re-injected after modulation or amplification, can be very small in the fibre, because the refractive index discontinuity between the outside world and the fibre mode

30 can be tiny. This suggests that bulk optical devices having near-zero insertion loss could be implemented for the first time. In contrast, the index step between a conventional fibre and air always causes some light to be

- 6 -

reflected at a fibre end face. Not only does this cause loss of light, but unwanted reflections can seriously destabilise any laser sources that they re-enter, and cause optical amplifiers to oscillate as lasers (a highly

5   undesirable event).

Guidance in a lower-index region is possible because the photonic band gap material of the fibre cladding can behave in a manner similar in some respects to a totally reflecting, perfect metal under some circumstances but,

10   unlike real metals, such a quasi-metal exhibits very low losses at optical frequencies. The photonic band gap material behaves like a metal when it exhibits a full two-dimensional photonic band gap; that is, when light propagating with a particular wavevector component along

15   the fibre and at a particular frequency sees, at all azimuthal angles, material having a band gap. Only certain wavelength bands are confined and guided down the fibre, those bands corresponding to the presence of full two-dimensional band gaps in the photonic crystal

20   cladding.

The wavevector component along the waveguide, known as the propagation constant β, determines whether light is propagating or evanescent in any part of the guide. If $\beta < kn$, the light propagates at an angle θ to the axis in

25   a material of refractive index n, where $\beta = kn \cos \theta$ and k is the vacuum wave constant. If $\beta > kn$, θ is imaginary and the light is evanescent. Conventional total internal reflection, with a core of index n_1 greater than the cladding index n_2, ensures the existence of a range of β

30   where light is propagating in the core while being evanescent in the cladding.

- 7 -

In contrast, light can be confined between two
multilayer dielectric stacks in a core of arbitrary
refractive index, if the stacks have a photonic band gap
for a range of β at a given optical frequency. We

5   identified two distinct regimes of photonic band gap
guidance. In the first, light propagates ($\beta < kn_1$) in the
layers of high index n_1 but is evanescent ($\beta > kn_2$) in the
layers of low index n_2. The high index layers act as
individual total internal reflection waveguides,

10   supporting bound modes at specific values of $\beta = \beta_m$.
Resonant tunneling between adjacent high-index layers
permits leakage of light through them, provided β lies
within the pass bands that open up around each β_m. The
widths of the pass bands depends on the strength of

15   coupling between the layers. Between the pass bands lie
band gaps; if a high-index core layer with a different
(maybe smaller) width supports a mode with β inside a band
gap, it is not resonant with the other layers and light
leakage by tunneling is frustrated. The mode is thus

20   strictly guided by the frustrated tunneling form of
photonic band gap guidance.

In the second regime of photonic band gap guidance,
light can propagate in all layers ($\beta < kn_2$). Band gaps
occur at the Bragg condition as a result of multiple

25   scattering and interference, leading to the Bragg form of
photonic band gap guidance.

In both forms of photonic band gap guidance, the
refractive index of the core can be chosen much more
freely than in total internal reflection guidance, because

30   the photonic band gap conditions depend only on the
properties of the cladding stacks. Guided modes can exist
with mode indices β/k that are lower than the "mean" index

- 8 -

of the stacks (the frustrated tunneling guidance case) or
even lower than the lowest index of the stacks (the Bragg
guidance case), conferring extra design freedom over total
internal reflection guidance, and allowing confinement
5   within a hollow core.

The substantially periodic cladding may have a
triangular lattice structure. The triangular lattice may
comprise air holes in a solid matrix.

Preferably, the regions of higher refractive index
10   consist essentially of silica. Materials other than silica
may also be used, including other silicate glasses and
soft glasses of different compositions. The fraction of
air in this part of the fibre needs to be relatively large
to exhibit a sufficiently broad band gap. Advantageously,
15   the fraction of air in the cladding is at least 15%, and
may be more than 30%, by volume based on the volume of the
cladding.

Whilst it is within the scope of the invention to
provide a region of lower refractive index that is of
20   elongate cross-sectional shape, it will generally be
preferred for the region to be of generally round cross-
section.

It should be understood that the fibre may include
more than one region of lower refractive index.

25   Preferably the region of lower refractive index
comprises a gas or a vacuum; the region of lower
refractive index may be at atmospheric pressure (or even a
higher pressure) but it may also be a low pressure region.
The gas is preferably air. The substantial confinement of
30   light to the region of lower refractive index means that
the photonic crystal fibre may be capable of transmitting
light at powers, and/or at wavelengths, at which it is not
possible to transmit light in conventional fibres.

- 9 -

In an example of the invention described below the region of lower refractive index is of substantially round cross-section and has a diameter that is about 2½ times the shortest period of the cladding. Larger or smaller

5   diameters may, however, be used. Preferably the region of lower refractive index has a longest transverse dimension at least 1.5 times longer, and preferably at least 2 times longer, than a single, shortest period of the cladding.

The actual cross-sectional dimensions of the region

10   of lower refractive index will depend upon the wavelength(s) of light to be guided along the fibre, the period of the cladding and, in some cases, the refractive index of the region of lower refractive index. In an example of the invention described below the region of

15   lower refractive index is of generally round cross-section and has a diameter of about 15 µm. Usually it will be preferred that the region of lower refractive index has a longest transverse dimension of at least 9 µm, and preferably at least 12 µm.

20   A strong interaction may be possible between light in the guided mode and the fluid which may form the lower index waveguiding core; that interaction could be useful, for example, for gas sensing and monitoring. The lower index region may comprise a material having a non-linear

25   optical response, whereby light may be generated or modulated by non-linear processes in the lower index region.

Optical properties of the fibre can be accurately computed once the fibre size is fixed. The photonic band gap of the periodic fibre cladding can extend over a broad

30   range of frequencies; however, in general, the mode will be guided in the lower-index region only over a relatively narrow range of frequencies. The narrowband performance of

the fibre suggests that it should be useful as a spectral filtering device.

A photonic crystal fibre according to the invention may alternatively be defined in terms of the region of lower refractive index being large enough to support at least one guided transverse mode. Thus according to the invention there is provided a photonic crystal fibre comprising a region of substantially uniform, lower refractive index which is substantially surrounded by cladding which includes regions of higher refractive index and which is substantially periodic, characterised in that the region of lower refractive index is large enough to support at least one guided transverse mode.

Preferably, the photonic crystal fibre is a single-mode fibre.

A wide variety of optical devices incorporating a photonic crystal fibre according to the invention can be envisaged. As has been described, such a device could, for example, comprise a sensor that is capable of sensing a property of the gas of which the region of lower refractive index is comprised or it could comprise a spectral filtering device. Other optical devices which could include such a fibre include, for example, an optical amplifier or a laser.

Optical fibres are widely used in the telecommunications industry. A telecommunications system could include an optical fibre according to the invention and such a telecommunications system could be included in a telecommunications network.

Also according to the invention, there is provided a method of making an optical fibre, comprising the following steps:

- 11 -

(a)   forming a stack of canes, the stack including at
least one truncated cane which defines a cavity in the
stack;

(b)   drawing the stack into a fibre having an
5   elongate cavity.

Such an approach represents a modification of a
fabrication process previously disclosed for photonic
crystal fibres; in the known process there are no
truncated canes in the stack. However, if canes are
10   removed from the middle of such a stack and, especially if
two or more canes that are adjacent to one another are
removed, the resulting preform may no longer be stable and
self-supporting. Even removing one cane may, however,
give rise to a problem. In the method according to the
15   invention, lengths of cane, or bundles of canes, that have
the shape and size required for the final hole are
embedded within the stack of canes at the opposite ends of
the stack. The lengths of those embedded canes are such
that they do not meet in the middle of the stack.
20   Instead, a length (which may be approximately 15cm)
intermediate the ends of the preform is left with the
required large air hole, supported from either end in a
stable fashion. After the (complete) preform is drawn down
into a fibre (in one or more stages), only the fibre from
25   the central part of the preform is retained.

The method according to the invention could be useful
for constructing a wide variety of fibre structures, which
would otherwise be difficult to manufacture. Thus the
method is not restricted only to a method of making a
30   photonic crystal fibre according to the invention.

It should be understood that the method may involve
forming a stack of canes that defines more than one cavity

in the stack.   In that way a fibre with more than one
elongate cavity may be formed.

    Preferably, the cavity has a transverse dimension
greater than the corresponding transverse dimension of any
5   of the canes.   The cavity may have a transverse dimension
greater than the sum of the corresponding dimensions of
any two of the canes.

    Preferably, the stack of canes comprises canes which
are capillaries, which may form a triangular array.   The
10 capillaries may be filled with air or with a material
other than air; they may be partially or completely
evacuated.   The cavity may have a cross-sectional area
substantially equal to or greater than the cross-sectional
area of a bundle of four, and more preferably a bundle of
15 seven, of the canes.

    Also according to the invention there is provided a
method of transmitting light along a photonic crystal
fibre, the fibre being a fibre as defined above.

    By way of example, an embodiment of the invention
20 will now be described, with reference to the accompanying
drawings, of which:

        Fig. 1   is a schematic cross-section of an optical
                        fibre;

        Fig. 2   shows part of a preform suitable for making
25   the optical fibre of Fig. 1;

        Fig. 3   is a scanning electron microscope
                        photograph of an actual fibre of the kind
                        illustrated schematically in Fig. 1;

        Fig. 4   shows an emission spectrum recorded from a
30   fibre such as that shown in Fig. 3;

        Fig. 5   shows another emission spectrum recorded
                        from a fibre such as that shown in Fig. 3,

- 13 -

the spectrum in this instance being

recorded only for the red spectral region.

Light can be guided in an "air-mode" in a hole in a
fibre waveguide such as that shown in Fig. 1. The fibre
5   comprises a cladding formed by a triangular array of
fused, elongate tubes 1, which have been drawn from silica
capillaries and contain longitudinal air holes 2. The
capillaries are of circular cross-section resulting in
interstitial holes 3 between the tubes 1. The fibre also
10   comprises a core in the form of a large air hole 4 at its
centre. The air hole 4 is formed in this example, as
described below, by omitting a bundle of seven capillaries
from part of the fibre's preform and is therefore the size
of seven unit cells of the cladding material; the hole 4
15   is therefore much larger than the holes 2 in the fused
tubes 1 and also very much larger than the interstitial
holes 3. Fibres formed by omitting just a single cane
were observed not to guide modes in the air hole.

It is useful to consider why it is that photonic
20   crystal fibres with similar cladding parameters but with a
defect formed by omitting just a single capillary have not
been found to support guided modes. The number of guided
modes that a conventional fibre can support is determined
by the core-cladding index difference and the size of the
25   core. This follows fundamentally from phase-space
arguments closely analogous to well-known density-of-
states calculations in solid-state physics, and leads to
the result that the approximate number of spatial modes in
a convention fibre is:

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$$N_{conv} = \frac{r_{co}^2 k^2 \left(n_1^2 - n_2^2\right)}{4}$$ (1)

- 14 -

where r_{co} is the core radius, n_1 and n_2 the core and
cladding refractive indices, and k the vacuum wavevector.
(There are of course two polarization states per spatial
mode.) In a hollow-core photonic crystal fibre, a similar
expression may be derived for the approximate number of
spatial modes present in the hollow core:

$$N_{PBG} = \frac{r_{co}^2 \left(\beta_H^2 - \beta_L^2\right)}{4} \text{ or } \frac{r_{co}^2 \left(k^2 n_1^2 - \beta_L^2\right)}{4} \qquad (2)$$

where β_H and β_L are the upper and lower edges of the
photonic band gap at fixed optical wavelength, and the
second expression applies if the upper photonic band gap
edge extends beyond the maximum core wavevector, i.e., if
$k^2 n_1^2 < \beta_H^2$. Theory shows that, for a typical triangular
array of air holes in silica, the photonic band gap width
$\Delta\beta = \beta_H - \beta_L$ is a small fraction of its average position
$\beta_{av} = (\beta_H + \beta_L)/2$. For example, at $\beta_{av}\Lambda = 9$, $\Delta\beta\Lambda = 0.2$ and
taking $r_{co} = \Lambda/2$ for a single missing stack cane (Λ is the
inter-hole spacing) the expected number of spatial modes
is 0.23, making it unlikely that any air-guided mode will
be seen. On the other hand, if seven stack canes are
removed, the hollow core area is increased by a factor of
7, the core radius by a factor of $\sqrt{7}$ and the expected
number of spatial modes becomes 1.61. This suggests that
a seven-cane hollow core will support at least a single
transverse mode (two polarization states) and perhaps a
second transverse mode. These predictions are consistent
with our observations that fibres made with a single-cane
air hole do not support air-guided modes, whereas those
with a seven-cane hole guide light in one or two modes.

The pitch, lattice, and filling fraction of the
cladding region are chosen so as to exhibit a 2-
dimensional photonic band gap (see, for example, T.A.

- 15 -

Birks, P.J. Roberts, P. St. J. Russell, D.M. Atkin and T.J
Shepherd, "Full 2-d photonic bandgaps in silica/air
structures", Electron. Lett. 31 1941 (1995)). Light
within the hole 4 is trapped by the photonic band gap of
5 the surrounding material. Consequently, the light cannot
propagate away from the fibre core but is constrained to
travel along the fibre axis, substantially confined to the
core, as a guided mode.

    In the fabrication process previously disclosed for
10 photonic crystal fibres, several hundreds of canes, at
least some of which may be capillary tubes, are stacked
together to form the required crystal structure on a
macroscopic scale. Those canes typically have an external
diameter of the order of a millimetre. The entire stack is
15 then held together while being fused and drawn down into
fibre using an optical fibre drawing tower. That standard
procedure will not result in a preform which is stable or
self-supporting if it has the required large air hole in
the middle.

20   The preform shown in part in Fig. 2 provides a
solution to that difficulty. Two truncated lengths 6 of
stacked canes, are embedded within the stack of canes 5.
The truncated canes 6 are present at both ends of the
preform but they do not meet in the middle of the stack.
25 Instead, they define a short cavity 7. The innermost canes
5, which would otherwise collapse into the cavity, are
thus supported from both ends in a stable fashion. A
transverse cross-section through the full preform, and
through the cavity 7, thus has a form similar in shape to
30 the schematic in Fig. 1. The preform is drawn down into
fibre (in one or more stages) in the usual manner. Once
the fibre has been drawn, only that fibre from the central
part of the preform is retained.

- 16 -

The fibre of Fig. 3 was fabricated using this technique. It can be seen that the structural integrity of hole 4 has been maintained in the drawing process. In general, the high quality of the lattice of the fibre of

5   Fig. 3 is striking and the fibre cross-section closely resembles the schematic of Fig. 1. Some defects 9 can be seen, but their influence is not sufficiently deleterious to prevent air-mode guidance in the fibre.

In a particular example of the invention, the fibre

10 is formed from 331 silica capillaries each of circular cross-section and having an external diameter of 0.8 mm and an internal diameter of about 0.7 mm. The capillaries were arranged as described with reference to Fig. 2 with seven capillaries in the centre of the array being omitted

15 over a middle part of their lengths so as to define a cavity of length 15 cm. The preform was drawn into a fibre as described above; the resulting fibre had an external diameter of 90 μm and a central hole 4 of diameter 15 μm.

20   Initial characterisation was carried out by holding ~3 cm long samples vertically, illuminating them from below with white light (using a Tungsten halogen lamp), and observing the light transmitted through them in an optical microscope. The central air core was filled with

25 a single lobe of coloured light, its transverse profile being smooth, peaked in the centre and falling off to very low intensities at the glass-air boundary. A significant amount of white light was present in the periodic cladding, and it was striking how colourless it appeared

30 in comparison to the mode trapped in the core. Different colours of vacuum-guided mode were seen, depending on the overall fibre size and the drawing conditions used. The precise colour was sometimes hard to assign by eye, and in

- 17 -

fact in some cases appeared to be a mixture of different colours, e.g., red and blue. For appropriate excitation with the white light source, a few samples supported a similarly coloured two-lobed mode, which we attribute to a second guided mode falling in the same band gap as the first.

The transmission spectra through the air core of lengths of fibre were measured by linking the microscope via a conventional multimode fibre to an optical spectrum analyser. The spectral dependence of the waveguiding in the air hole demonstrated that several well-defined bands of transmission were present, covering the whole visible spectrum and extending into the infrared. Each of those bands corresponded to a full 2-D photonic band gap, and is related to higher order Bragg conditions in the photonic crystal cladding. Since the pitch of the crystal was large in comparison to the wavelength, the photonic band gaps responsible for the guidance were of high order. By selecting lengths of fibre which had been shown to support a guided mode at appropriate wavelengths, we excited this mode using laser sources. Within each transmission band, losses were small or zero over fibre lengths of several centimetres, whereas between those bands the losses were much larger, as expected in the absence of photonic band gap effects. The length was limited by fluctuations in the fibre parameters, which caused the wavelengths of the guided modes to vary along the length of fibre. In other fibres, which do not support guided modes at that wavelength, the laser light leaked entirely into the cladding after propagating only a fraction of a centimetre.

Laser light guided in the air formed a stable, smoothly varying single lobed pattern in the far field.

By incorporating a guiding length of fibre into one arm of
a Mach-Zehnder interferometer, we confirmed that the laser
light transmitted through the guiding core had a high
degree of spatial coherence, giving high visibility

5   fringes at the interferometer output. That would not be
the case if there were many waveguide modes excited in the
fibre core.

The optical transmission spectra of the fibre were
examined and are shown in Figs. 4 and 5 in each of which

10   transmitted intensity is plotted against wavelength. The
optical transmission spectra shown in Figs. 4 and 5,
demonstrate that the fibre supports air-modes at a number
of wavelengths; there are strong transmission peaks around
490 nm, 610 nm and 810 nm. There also appears to be, in

15   Fig. 4, evidence of ultra-violet transmission at around
440 nm. It may be noted that the transmission pass-bands
are narrow compared with those of conventional optical
fibres.

In the example of the invention described with

20   reference to the drawings the region of lower refractive
index is air and the fibre is made by forming a stack of
canes which includes truncated canes to define a cavity in
the stack. It is within the scope of the invention for
the cavity in the stack to be filled partly or completely

25   with a material other than air and/or with one or more
canes of lower refractive index than the canes used to
form the cladding.

Where reference is made in this specification to
"light" it should be understood that the term "light"

30   includes electromagnetic radiation at frequencies outside
the visible spectrum.